

AN OPTICAL MODEL FOR ESTIMATING THE UNDERWATER LIGHT FIELD FROM REMOTE SENSING*

Cheng-Chien Liu¹ and Richard L. Miller²

¹NRC Research Associate, NASA, Stennis Space Center, MS 39529 USA

²NASA, Earth Science Application Directorate, Stennis Space Center, MS 39529 USA

ABSTRACT

A model of the wavelength-integrated scalar irradiance for a vertically homogeneous water column is developed. It runs twenty thousand times faster than simulations obtained using full Hydrolight code and limits the percentage error to less than 3.7%. Both the distribution of incident sky radiance and a wind-roughened surface are integrated in the model. Our model removes common limitations of earlier models and can be applied to waters with any composition of the inherent optical properties. Implementation of this new model, as well as the ancillary information required for processing global-scale satellite data, is discussed. This new model is fast, accurate, and flexible and therefore provides important information of the underwater light field from remote sensing.

1.0 INTRODUCTION

One major goal of satellite ocean color is to assess the role of the ocean in the global carbon cycle and to examine the factors that affect global climate change (Hooker *et al.*, 1992). Although phytoplankton account for less than 1% of the total global plant biomass, they contribute to about 40% of global productivity (Falkowski, 1994) and turn over carbon and nutrients more rapidly than terrestrial plants (Summerhayes, 1996). To attain the goal of analyzing ocean carbon flux, the amount and distribution of ocean phytoplankton must be estimated from space. Many efforts to date have focused on relating the radiative signals to pigment concentration (Gordon *et al.*, 1988; O'Reilly *et al.*, 1998; Carder *et al.*, 1999). Maps of satellite-derived pigment concentration (e.g., biomass) have been widely used to estimate global ocean carbon content and productivity (Longhurst, 1995; Platt *et al.*, 1995). However, rates of phytoplankton photosynthesis are regulated by many factors including light availability. Hence, an accurate estimation of ocean primary production and carbon flux requires a thorough description of the underwater light field.

A common approach for calculating the underwater light field is based on satellite-derived estimates of the diffuse attenuation coefficient (e.g. $K_d(490)$) (Yeh *et al.*, 1997). Spectral information is formulated based on ratios of water-leaving radiance to $K_d(490)$. Only an average value of K_d over the first optical attenuation depth at one spectral waveband can be obtained using this approach. Most phytoplankton-based applications, therefore, relate empirical models of water content, such as the satellite-derived chlorophyll concentration (Chl), to the spectral value of K_d (Sathyendranath, 1989).

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Recently, Liu *et al.* (2001) discussed the sources of error in a K -based model. They proposed an alternative fast and accurate model to calculate the underwater scalar irradiance, $E_0(z)$. Their model was based on a large number of simulations compared to results from Hydrolight (Mobley and Sundman, 2001). The model considered both the distribution of incident sky radiance and a wind-roughened surface and could be applied to Case 1 waters as well as gelbstoff-rich Case 2 waters. However, the inherent optical properties (IOPs) were parameterized as a function of Chl with a limited range of 0 to 10.0 $\text{mg}\cdot\text{m}^{-3}$. In addition, the Petzold's average particle phase scattering function was assumed and the spectral range limited to 400 – 700 nm. These limitations must be removed to apply the model to estimate the underwater light field from remote sensing.

This work extends the model of Liu *et al.* (2001) to the development of a new model of the wavelength-integrated scalar irradiance for a vertically homogeneous water column. This new model removes the original model limitations and yet remains both the advantages of speed and accuracy. Comprehensive model-to-model comparisons were made to demonstrate that the new model could be applied to waters with any composition of IOPs. Implementation of this new model, as well as the ancillary information required for processing the global satellite data are discussed below.

2.0 PARAMETERIZING THE INHERENT OPTICAL PROPERTIES

The earlier model is mainly limited by the parameterization of IOPs (e.g., Chl and the wavelength, λ). We started the new model formulation by reexamining the selection of main variables for parameterizing IOPs.

The numerical optical model is simply a model that converts the IOPs to the apparent optical properties (AOPs). Its performance relies on how accurate and efficient the IOPs are specified. All IOPs can be derived from two principle IOPs: the absorption coefficient a and the phase scattering function $\beta(\psi)$ (Haltrin, 1999), where ψ is the scattering angle. The key to our model is to construct a look-up table (LUT) for quick reference to the vertical profile of the average cosine $\bar{\mu}(z)$. These two principle IOPs should be selected as the main variables in the LUT. However, $\beta(\psi)$ describes the probability of scattering in the ψ direction, which varies from a symmetric distribution (molecular scale) to a heavily peak distribution in the forward direction (large particle). To consider a large range of the distribution of $\beta(\psi)$, it is necessary to find an accurate and efficient way to parameterize $\beta(\psi)$.

An analytical phase function for ocean water was proposed by Fournier and Forand (1994), parameterized as a function of the backscattering fraction BF , where

$$BF \equiv \frac{b_b}{b}. \quad (1)$$

A large range in $\beta(\psi)$ can be obtained by varying the value of BF . For example, $BF=0.0183$ provides a very good fit to the Petzold's average particle phase scattering function, while $BF=0.5$ yields the pure water phase function. This function has been integrated into Hydrolight as a standard method for specifying $\beta(\psi)$ (Mobley and Sundman, 2001).

Based on the work of Liu *et al.* (2001) a LUT with two variables BF (0.0001 – 0.5) and ω_0 (0.01 – 0.99) was constructed for quick reference to a set of parameters (B_0, B_1, P, B_2, Q) used by the McCormick five-parameter model (McCormick, 1995)

$$\frac{1}{\bar{\mu}(\zeta)} = B_0 + B_1 \exp(-P\zeta) + B_2 \exp(-Q\zeta). \quad (2)$$

Each profile of $\bar{\mu}(z)$ is obtained by assuming a black sky a unit light source in Quad_i with 10 quadrants in the plane of the Sun toward the Sun's direction (Liu *et al.*, 2001). The different distribution of sky radiance and the influence of a wind-roughened surface can both be considered by following the approach of Liu *et al.* (2001). A section of the LUT is given in Table 1, where the Pearson correlation coefficient PCC manifests how good the McCormick five-parameter model fits the vertical profiles of average cosine. Throughout the entire LUT, the average value of PCC is 0.999577 and the lowest value is 0.980118.

Table 1. A section of the model Look-Up Table (LUT).

Quad _i	BF	ω_0	B_0	B_1	P	B_2	Q	PCC
0°~5°	0.018	0.31	1.119133	0.086067	0.087585	0.017142	0.589276	0.999981
5°~15°	0.018	0.31	1.119114	0.073322	0.107362	0.016351	0.647022	0.999977
15°~25°	0.018	0.31	1.119486	0.062006	0.236405	-0.001879	0.236448	0.999166
25°~35°	0.018	0.31	1.114392	0.057128	0.324473	-0.040133	0.039546	0.998720
35°~45°	0.018	0.31	1.118637	-0.179313	0.089442	0.129340	0.269664	0.999598
45°~55°	0.018	0.31	1.119143	-0.261702	0.100093	0.128522	0.350085	0.999912
55°~65°	0.018	0.31	1.121492	-0.561937	0.134360	0.337626	0.281429	0.999969
65°~75°	0.018	0.31	1.121764	-0.582089	0.138694	0.221943	0.434598	0.999989
75°~85°	0.018	0.31	1.124118	-0.885466	0.170924	0.363883	0.454816	0.999959
85°~90°	0.018	0.31	1.125022	-1.013489	0.187065	0.304746	0.660470	0.999960
0°~5°	0.028	0.65	1.373320	0.271932	0.161337	0.021968	0.882993	1.000000
5°~15°	0.028	0.65	1.373073	0.253397	0.172978	0.025184	0.847033	0.999999
15°~25°	0.028	0.65	1.372813	0.215010	0.200954	0.032258	0.809092	0.999997
25°~35°	0.028	0.65	1.373503	0.011846	1.824845	0.193428	0.307510	0.999996
35°~45°	0.028	0.65	1.372300	-0.100636	0.131081	0.223320	0.422338	0.999807
45°~55°	0.028	0.65	1.372434	-0.224350	0.156887	0.252826	0.511613	0.999595
55°~65°	0.028	0.65	1.372819	-0.420876	0.181149	0.343479	0.534423	0.999893
65°~75°	0.028	0.65	1.373261	-0.572023	0.197543	0.339691	0.712891	0.999981
75°~85°	0.028	0.65	1.374038	-0.807693	0.221049	0.386052	0.861710	0.999987
85°~90°	0.028	0.65	1.375087	-1.010264	0.243537	0.375172	1.222987	0.999981

3.0 MODEL VALIDATION

Various models of IOPs were employed to examine whether the new LUT could provide a fast and accurate simulation of $E_0(z)$ for any composition of IOPs in a vertically homogeneous water column.

3.1 HISTORICAL MODEL OF CASE 1 WATERS

A set of bio-optical models of IOPs is widely used for Case 1 waters, including the absorption coefficient (Prieur and Sathyendranath, 1981; Morel, 1991)

$$a(z; \lambda) = a_w(\lambda) + 0.06a_c^*(\lambda)Chl^{0.65} + F \cdot 0.06 \cdot a_c^*(440)Chl^{0.65} \exp(-0.014(\lambda - 440)), \quad (3)$$

the scattering coefficient (Gordon *et al.*, 1983; Morel, 1991)

$$b(\lambda) = b_w(\lambda) + 0.30 \left(\frac{550}{\lambda} \right) Chl^{0.62}, \quad (4)$$

and the *normalized phase scattering function* $\tilde{\beta}$ (Mobley, 1994)

$$\tilde{\beta}(\psi; \lambda) = \frac{b_w(\lambda)}{b(\lambda)} \tilde{\beta}_w(\psi) + \frac{b_p(\lambda)}{b(\lambda)} \tilde{\beta}_p(\psi; \lambda). \quad (5)$$

$a_w(\lambda)$, $b_w(\lambda)$ and $a_c^*(\lambda)$ are given in the papers of Pope and Fry (1997), Smith and Baker (1981), and Morel (1988) respectively. F specifies how CDOM (colored dissolved color matter) relates to chlorophyll absorption at a reference wavelength of 440 nm. For Case 1 waters, F is frequently set to be a value of 0.2 (Prieur and Sathyendranath, 1981; Morel, 1991).

Two limitations of this set of models are often questioned. $\tilde{\beta}_p(\psi; \lambda)$ is calculated from the analytic Fournier-Forand phase function (Fournier and Forand, 1994) by specifying for the backscattering fraction for particle BF_p a value of 0.0183 to mimic the Petzold's average particle phase scattering function (Mobley and Sundman, 2001). A value of 0.0183 was noted to be too high for Chl greater than 2 or 3 ($\text{mg} \cdot \text{m}^{-3}$), as discussed, for example by Morel and Gentili (Morel and Gentili, 1991). In addition, the actual value of F may vary within a range around 0.2, even for the chlorophyll-dominated Case 1 waters (Liu *et al.*, 1999). To extend the applicability of this historical set of bio-optical models of IOPs, BF_p and F should be set as a free variable rather than a constant.

3.2 HALTRIN'S MODEL OF CASE 1 WATERS

Another model of IOPs for Case 1 waters was proposed by Haltrin (1999), which contains four components, including pure water, large particles (assumed to absorb like Chl and scatter like large particles), CDOM (assumed absorbing but non-scatter) and small particles (assumed non-absorbing but scatter). This model expresses spectral absorption, spectral scattering, and spectral angular scattering coefficients for each component through the concentration of

chlorophyll (Haltrin, 1999). It is important to note that two types of particles play a role in the scattering and the analytic Fournier-Forand phase function (Fournier and Forand, 1994) is employed by specifying the backscattering fraction for large particles BF_l a value of 0.00073 and small particles BF_s a value of 0.03933.

3.3 FOUR-COMPONENT MODEL OF CASE 2 WATERS

A more general model of IOPs for Case 2 waters exists that is similar to Haltrin's Case 1 model. However, the amount of each component is not constrained by Chl , the component of small particles represents minerals in waters that can both absorb and scatter light, and the backscattering fraction for large particles BF_l and small particles BF_s are not assumed to be a constant value.

The following comparison was made to examine whether our new LUT provides a fast and accurate simulation of $E_0(z)$ for IOPs described by various models. A total of 20 cases were compared by randomly specifying values for all parameters, including the solar zenith angle θ_s , cloudiness, surface wind speed V_{wind} , chlorophyll concentration Chl , CDOM ratio F , the backscattering fraction for large particles BF_l , the mineral concentration M , the mineral type, and the backscattering fraction for mineral particles BF_s (listed in the legend of Figure 1). Note that a set of absorption and scattering spectrum for various types of mineral, including Bukuta's brown earth ($M=1$), brown earth ($M=2$), calcareous sand ($M=3$), yellow clay ($M=4$) and red clay ($M=5$), is employed in Hydrolight (Mobley and Sundman, 2001). The wavelength-integrated scalar irradiance in the PAR range $E_{0,PAR}(z)$ was computed at 23 different depths ranging from 0 to 50 m for each case (Figure 1). The percentage error $\varepsilon_{\%}$ is calculated by

$$\varepsilon_{\%} = 10^{RMSE_{\log 10}} - 1, \quad (6)$$

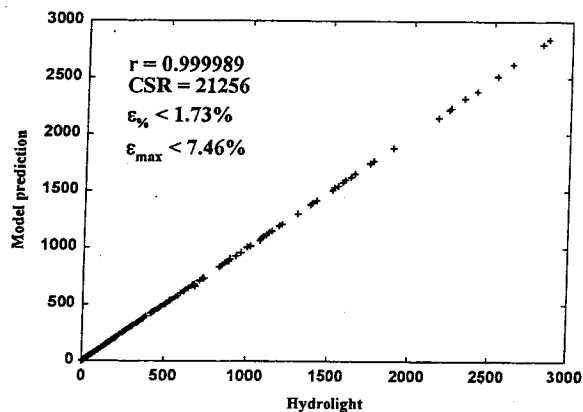
where the root-mean-square-error in log10 scale $RMSE_{\log 10}$ is defined by

$$RMSE_{\log 10} = \sqrt{\frac{\sum_{n=1}^N (\log_{10} E_{0,PAR}^{Model} - \log_{10} E_{0,PAR}^{Hydrolight})^2}{N}}. \quad (7)$$

This analysis provides the same emphasis on underestimates and overestimates.

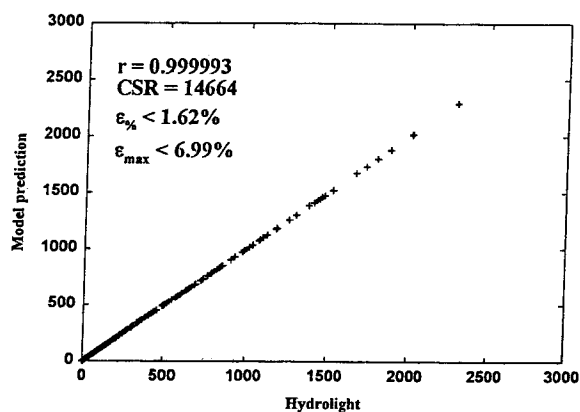
A very high correlation (r) as well as a large computational speed ratio (CSR) is obtained when comparing the results of our model to the results of a Hydrolight run with elastic scattering. The percentage error $\varepsilon_{\%}$ and the maximum relative error ε_{max} are both small. Figure 1 demonstrates that the new model can be applied to waters with various compositions of inherent optical properties.

(a) IOP's are specified by the historical model of Case 1 waters



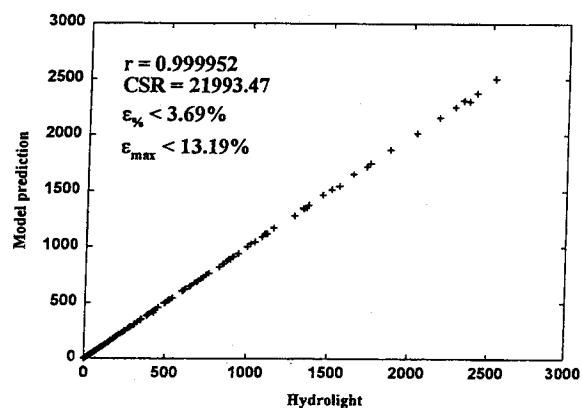
Parameters	θ_s (deg)	Cloud	V_{sw} ($M s^{-1}$)	Chl ($mg m^{-3}$)	F	BF _i
Range	0-90	0-1	0-15	0-10	0-2	0-0.1
	83.31	0.55	12.33	9.48	0.36	0.0688
	67.02	0.98	8.24	4.71	1.54	0.0384
	18.82	0.35	2.93	2.29	0.30	0.0685
	71.76	0.44	13.88	5.90	0.60	0.0060
	8.58	0.65	10.64	4.57	0.01	0.0818
	41.94	0.83	12.68	0.80	1.95	0.0361
	54.20	0.33	0.25	4.24	1.89	0.0708
	5.00	0.64	12.58	6.96	1.65	0.0704
	15.03	0.38	13.89	4.71	1.07	0.0074
	44.10	0.96	14.82	9.71	0.55	0.0945
	22.74	0.55	1.57	1.25	1.27	0.0482
	65.68	0.55	11.48	1.55	1.56	0.0852
	57.87	0.31	13.02	4.79	0.76	0.0314
	1.11	0.86	12.70	1.34	1.38	0.0070
	48.67	0.30	5.69	6.65	0.09	0.0926
	47.49	0.55	11.83	0.48	0.30	0.0766
	8.56	0.12	7.97	7.36	1.33	0.0367
	78.87	0.50	5.21	5.86	0.48	0.0331
	82.55	0.29	2.17	1.46	0.53	0.0041
	88.39	0.11	9.27	5.55	0.66	0.0878

(b) IOP's are specified by the Haltrin's model of Case 1 waters



Parameters	θ_s (deg)	Cloud	V_{sw} ($M s^{-1}$)	Chl ($mg m^{-3}$)
Range	0-90	0-1	0-15	0-5
	46.41	0.34	13.09	1.68
	13.63	0.62	5.97	2.73
	49.85	0.74	14.20	3.56
	82.91	0.92	5.24	0.12
	86.58	0.94	4.93	1.65
	45.98	0.69	9.02	0.65
	55.88	0.92	14.85	2.38
	59.96	0.80	13.11	1.76
	4.43	0.84	5.20	0.59
	0.36	0.09	2.30	4.93
	14.10	0.82	0.52	2.34
	34.47	0.51	14.09	2.10
	32.91	0.39	12.00	0.24
	64.22	0.46	3.12	4.84
	16.66	0.09	14.33	1.47
	57.72	0.80	9.19	2.22
	86.75	0.19	0.82	1.97
	56.20	0.71	1.56	3.83
	80.64	0.93	2.87	4.95
	76.04	0.80	13.51	0.10

(c) IOP's are specified by the four-component model of Case 2 waters



Parameters	θ_s (deg)	Cloud	V_{sw} ($M s^{-1}$)	Chl ($mg m^{-3}$)	F	BF _i	M ($g m^{-3}$)	Mineral Type	BF _i
Range	0-90	0-1	0-15	0-10	0-2	0-0.183	0-1		0.1183
	85.58	0.77	8.14	4.36	0.16	0.0061	0.03	2	0.0363
	78.84	0.08	13.63	0.16	0.88	0.0112	0.85	4	0.0208
	17.47	0.82	1.96	4.57	1.74	0.0168	0.58	4	0.0826
	66.5	0.63	2.41	0.44	0.31	0.0106	0.96	1	0.0778
	57.23	0.7	8.47	0.4	0.86	0.0087	0.07	4	0.0547
	84.3	0.46	10.93	7.36	0.91	0.0031	0.44	5	0.1179
	1.64	0.24	5.08	3.48	0.83	0.0012	0.08	4	0.029
	76.83	0.36	2.55	1.88	0.44	0.0165	0.06	5	0.0541
	17.55	0.28	2.81	5.31	1.76	0.0013	0.18	3	0.0984
	35.86	0.85	10.37	0.6	0.59	0.0003	0.54	2	0.0962
	72.56	0.45	6.22	4.51	0.69	0.0157	0.26	5	0.1024
	69.01	0.59	7.29	5.64	0.97	0.0159	0.76	3	0.1165
	31.31	0.27	5.9	6.76	1.92	0.0175	0.08	2	0.0294
	81.78	0.26	2.08	7.38	0.15	0.0089	0.5	2	0.0243
	4.19	0.65	2.1	7.55	1.24	0.0161	0.79	1	0.0802
	26.08	0.75	4.43	1.26	1.81	0.0025	0.65	5	0.1039
	13.28	0.21	14.02	8.48	0.14	0.004	0.48	3	0.037
	62.11	0.47	4.93	1.82	0.65	0.0091	0.15	4	0.0556
	10.26	0.58	10.81	6.19	0.72	0.0027	0.56	5	0.074
	15.32	0.91	5.48	5.96	0	0.0061	0.91	2	0.0342

Figure 1. Wavelength-integrated scalar irradiance in the PAR range $E_{0,PAR}(z)$.

4.0 CONCLUSION

Implementation of this new model to estimate the underwater scalar irradiance from remote sensing requires the ancillary data of surface conditions and the information of IOP's of water. The information of the ambient optical environment and the surface wind speed can be obtained by integrating observations from various satellite sensors. Although it is not possible, to date, to make a direct estimation of the phase scattering function $\beta(\psi)$ from space, recent advancements (Lee *et al.*, 2001) have enabled a more accurate retrieval of the absorption coefficient a and the back scattering coefficient b_b . We can estimate the scattering coefficient b from the satellite-derived chlorophyll based on the bio-optical model (Eq. 4) and calculate the backscattering fraction BF . With these IOP's and the ancillary data of surface conditions, this model is able to provide a new product of the vertical distribution of the scalar irradiance from remote sensing.

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